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(54) Abstract Title
Signal distortion correction using predistortion

(57)   The digital predistorter multiplies the input signal with coefficients obtained from look-up tables. To reduce the amount of storage required, the coefficients are stored in partial form and are either reconstituted by addition of a constant (44, Figure 3b not shown) prior to application to the input signal or the retrieved coefficients are applied directly to the input signal and the resulting modified signal is then combined with the original input signal (34, Figure 2a). The predistorter counteracts the effects of distortion in a signal output device such as a RF power amplifier. Also disclosed is a means for compensating for the effects of amplifier memory, using filters (figures 2c and 3c, now shown).
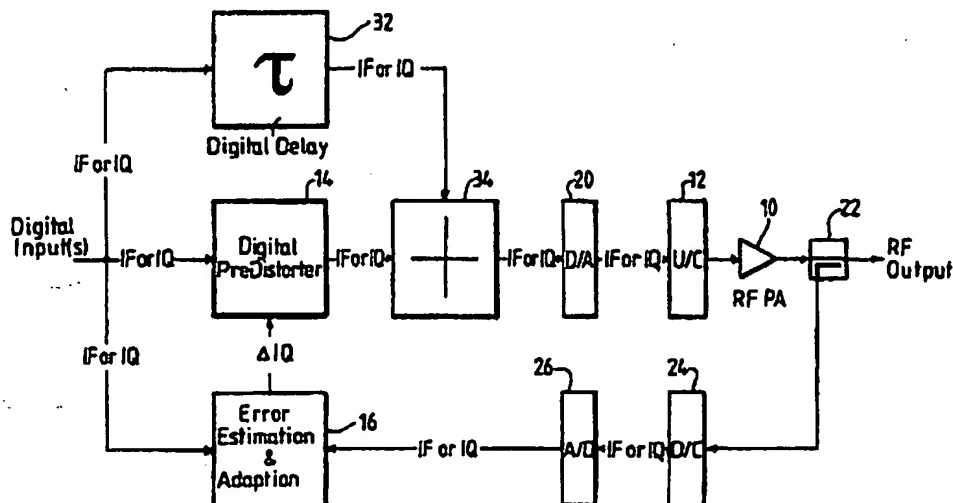
FIG.2a.

GB 2 376 613 A

RF
Output

22

10

12

RFPA

U/C

IF or
IQ

20

D/A

IF or
IQ

14

Digital
PreDistorter

IF or
IQ

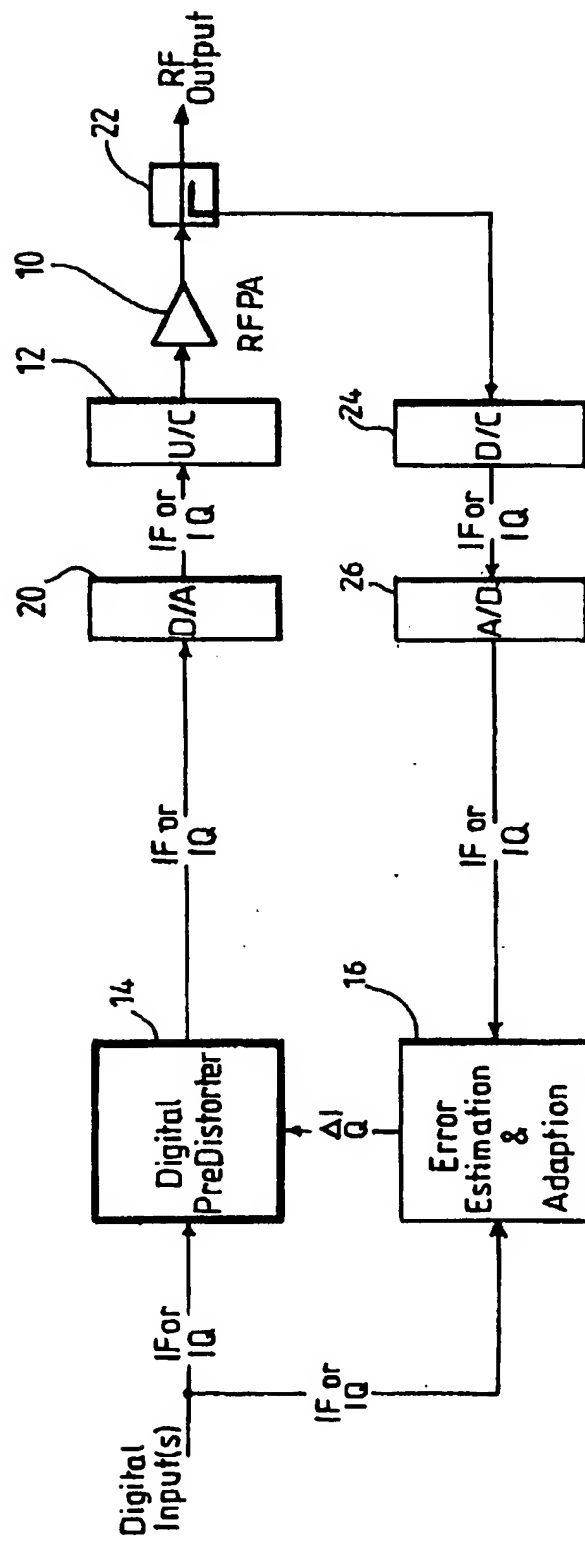Digital
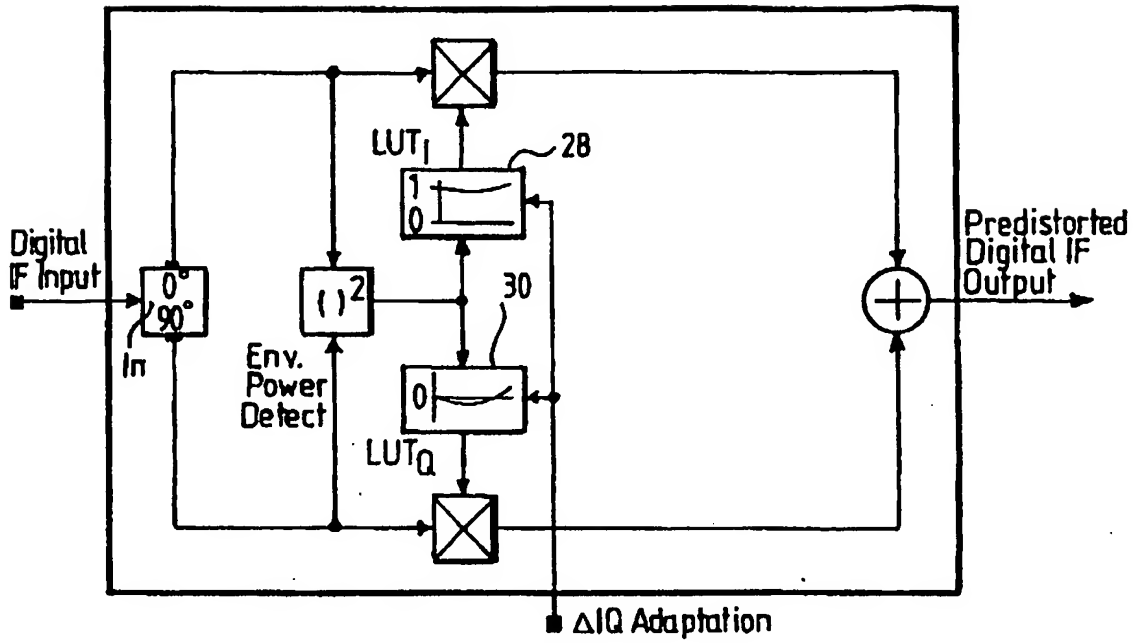Input(s)

24

D/C

IF or
IQ

26

A/D

IF or
IQ

16

Error
Estimation
&
Adaption

ΔI
Q

IF or
IQ

FIG.1a.

FIG.1b.
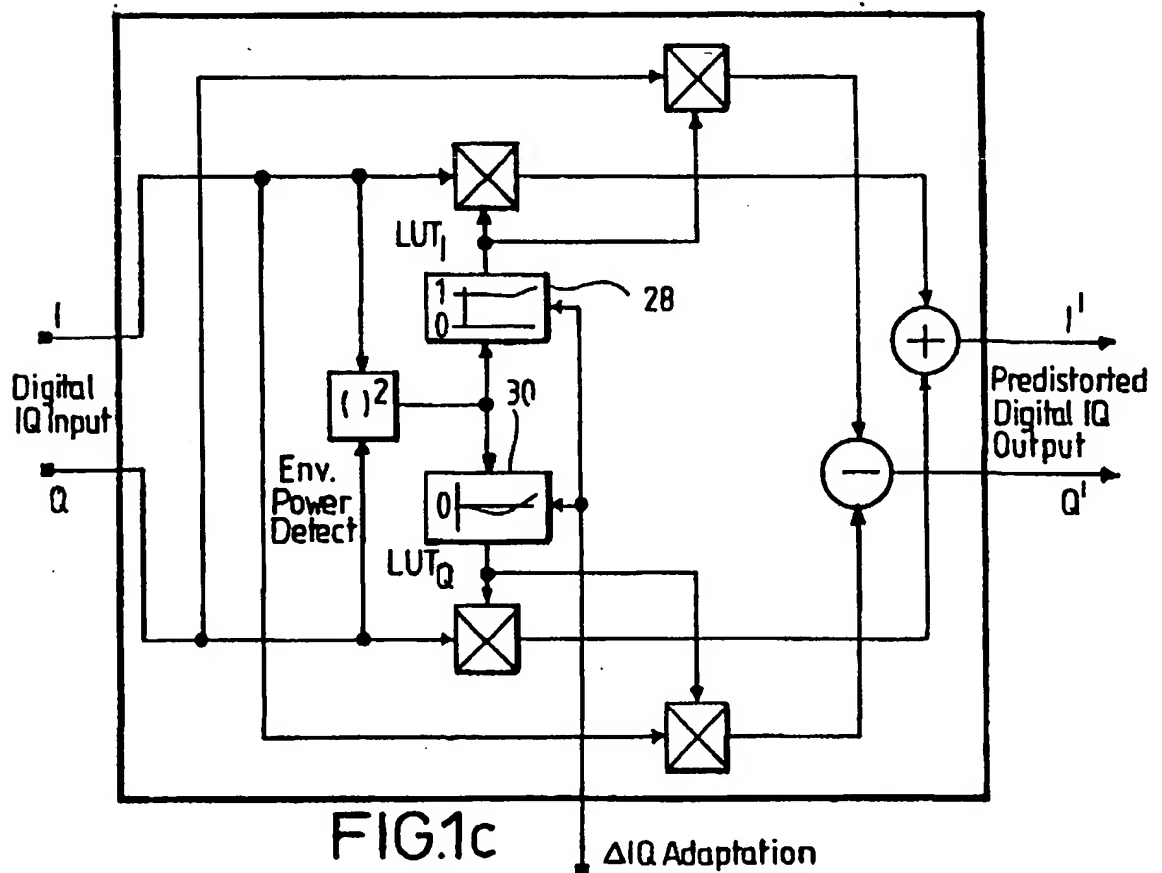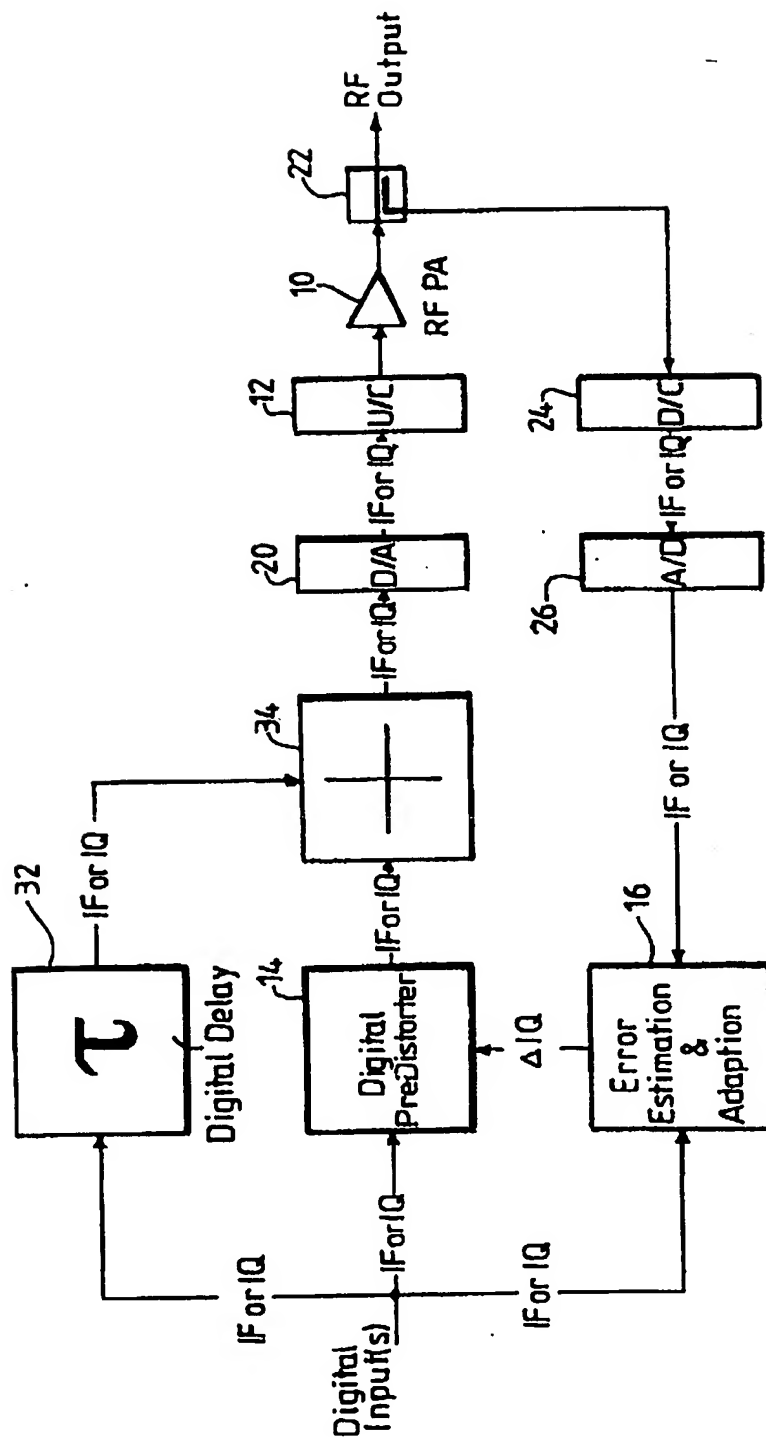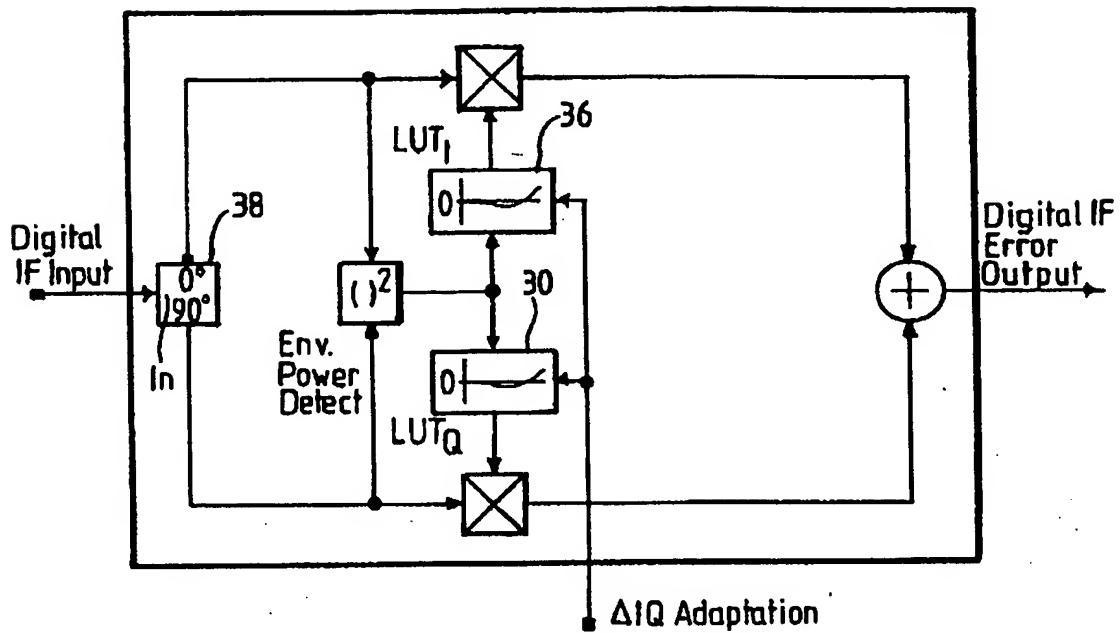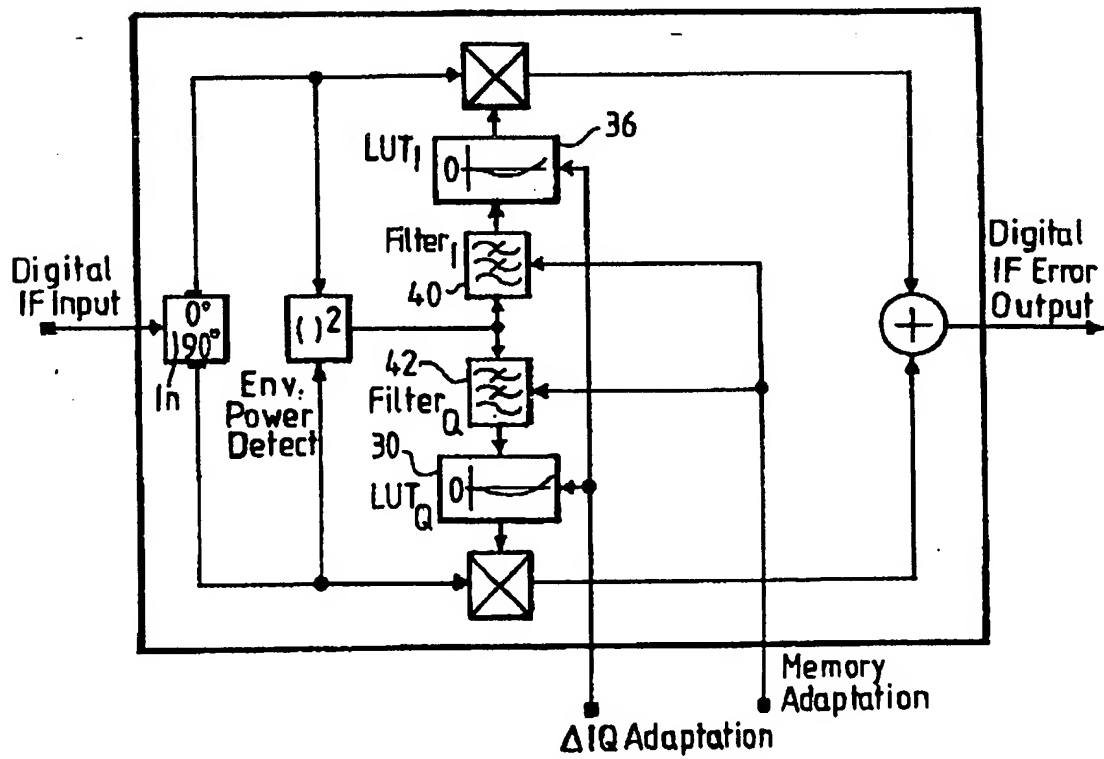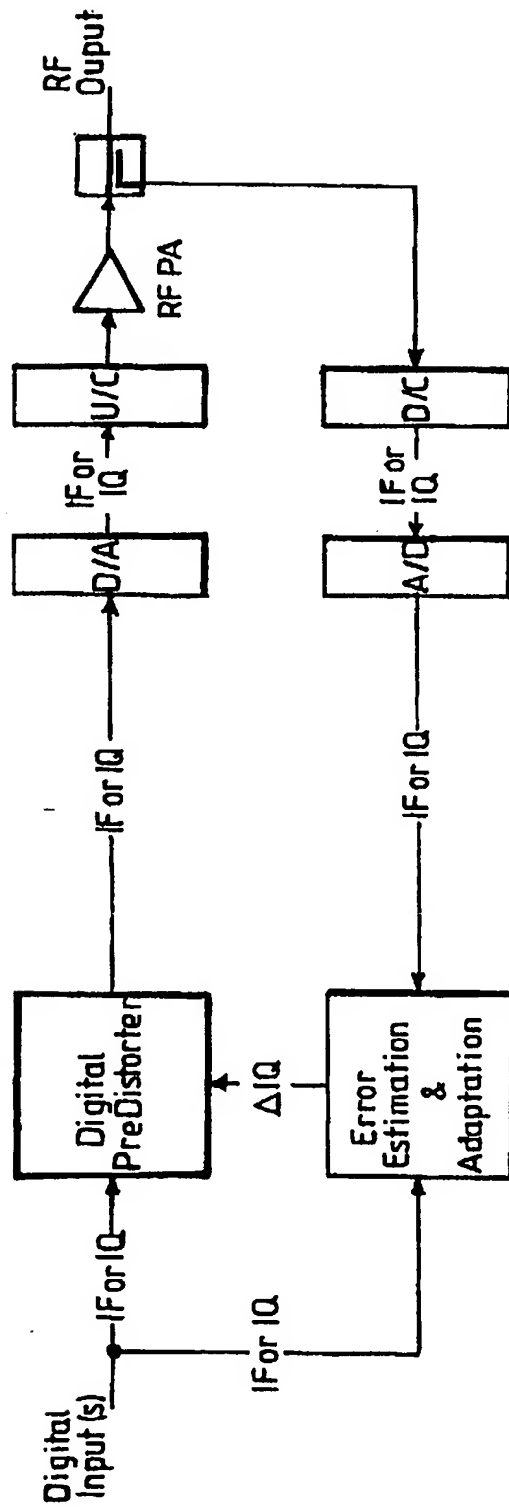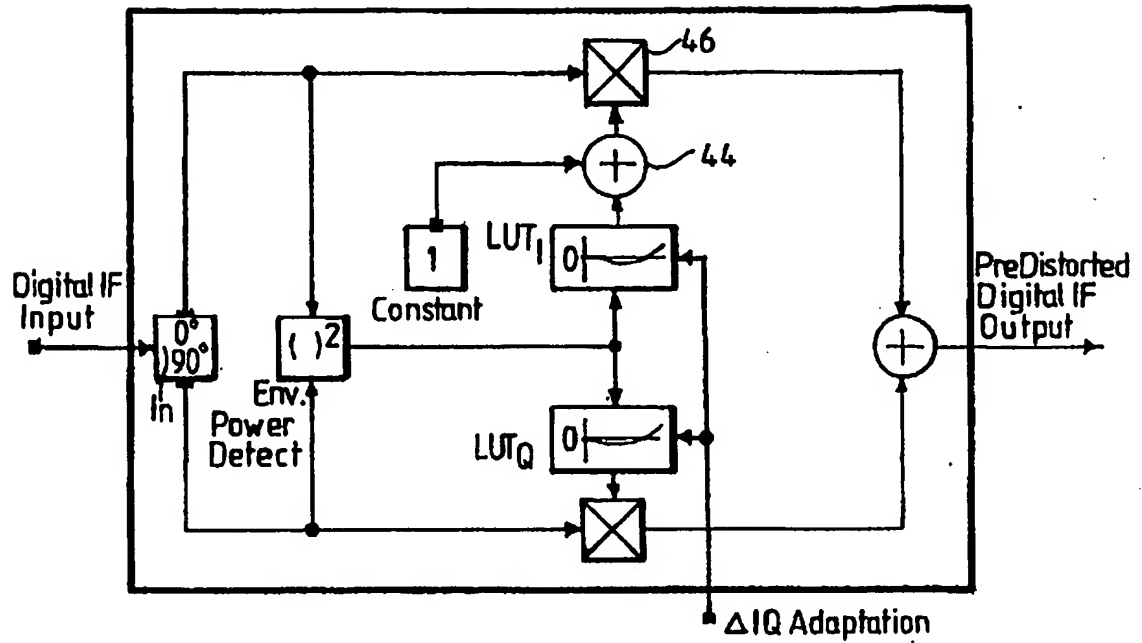

FIG.1c

FIG.2a.

FIG.2b.

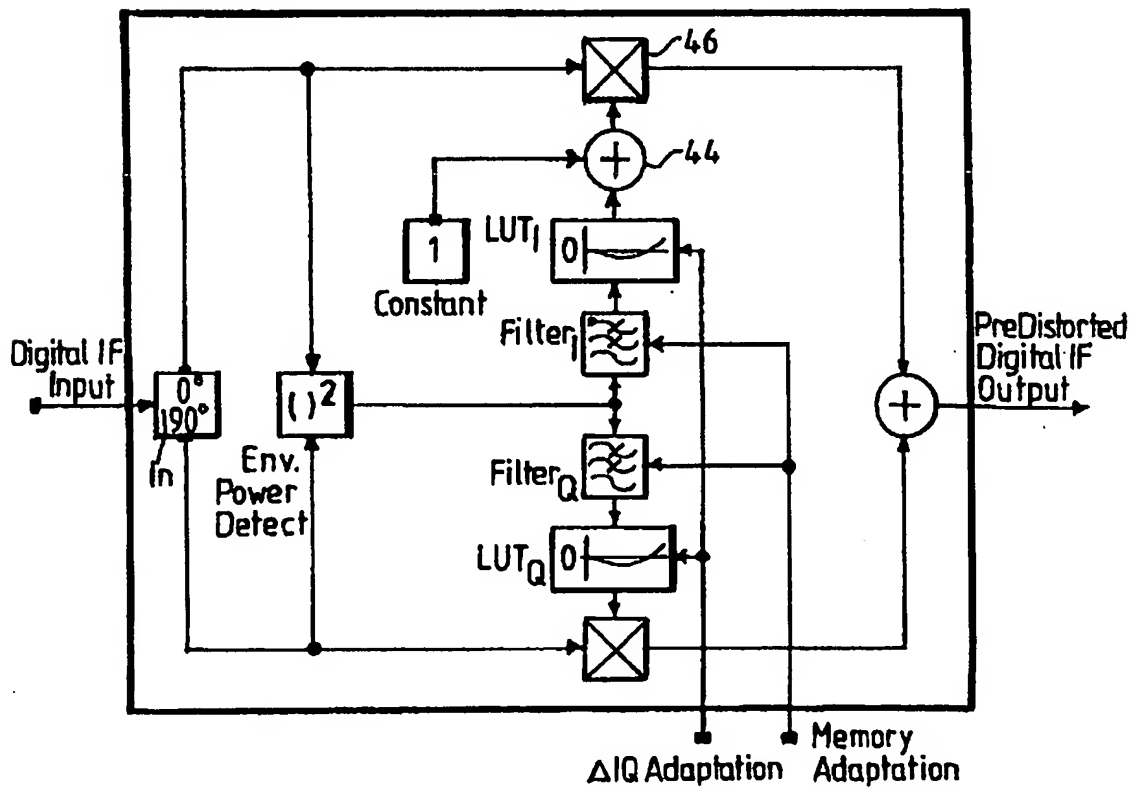
FIG.2c.

FIG.3a.

FIG.3b.

FIG.3c.

METHODS AND APPARATUS FOR SIGNAL DISTORTION CORRECTION

The invention relates to methods of, and apparatus for, correcting signal distortion by employing a group of adaption coefficients to adjust a consequential signal to ameliorate distortion in an output signal produced by signal handling equipment in response to an input signal. In particular, the distortion correction involved is the linearisation of the signal handling equipment.

The use of digital pre-distortion has significant flexibility benefits compared with conventional RF predistorters. In the case of a digital pre-distorter, a more sophisticated non-linearity may be formed without a significant increase in the required hardware complexity and all aspects of this non-linearity may be updated under automatic control. Additionally the accuracy of distortion measurement for adaptive control is normally much improved in a digital predistortion architecture compared to the RF pre-distorter architecture.

It is also beneficial to pre-distort for non-linear memory effects in a power amplifier. Memory effects result in the amplifier distortion characteristics being different at the same envelope level depending upon past history, for example following a large RF output pulse. Non-linear memory effects are a common observation in power amplifiers and manifest themselves as imbalanced distortion products around the wanted signal spectrum. Correction of memory effects becomes increasingly more important as the bandwidth of the wanted signal increases.

The performance of a digital pre-distortion linearisation system is limited largely by the resolution of the various parts of the digital system, for example:

1. The resolution of the data converters (A/D and D/A) used to sample the feedback signal or to supply the pre-distorted signal.

2. The size and resolution of the look-up tables.

3. The resolution of the signal processing (error estimation and adaption).

4. The resolution used in any input pre-processing or output post processing (e.g. digital up or downconversion, filtering).

The various resolutions used in each of these parts of the system need not be equal and indeed it is beneficial for them to differ from the standpoint of the optimum use of digital hardware resources, for example in an FPGA or ASIC implementation.

One object of the invention is to provide improved techniques for reducing the distortion of signals, for example techniques for performing predistortion linearisation.

According to one aspect, the invention provides apparatus for correcting signal distortion by employing a group of adaption coefficients to adjust a consequential signal to ameliorate distortion in an output signal produced by signal handling equipment in response to an input signal, the apparatus comprising means for using partial adaption coefficients in the adjustment of the consequential signal and means for correcting for the fact that the retrieved coefficients are partial to give the effect that adjustment of the consequential signal has been done using complete adaption coefficients.

The invention also consists in a method of correcting signal distortion by employing a group of adaption coefficients to adjust a consequential signal to ameliorate distortion in an output signal produced by signal handling equipment in response to an input signal, the method comprising using partial adaption coefficients in the adjustment of the consequential signal and correcting for the fact that the retrieved coefficients are partial to give the effect that adjustment of the consequential signal has been done using complete adaption coefficients.

Partial adaption coefficients can be smaller than complete adaption coefficients. This means that a partial adaption coefficient can be represented with fewer bits than a complete

adaption coefficient. Thus, partial adaption coefficients may require less storage, and hence this leads to a reduction in power consumption. For a given resolution, fewer bits may be required to specify a partial adaption coefficient compared to its corresponding complete adaption coefficient because partial adaption coefficients can be smaller than complete adaption coefficients. Thus, where a given number of bits is available to represent an adaption coefficient, the use of the partial form allows a greater resolution to be used for the adaption coefficient.

In one embodiment, the correction for the use of partial adaption coefficients is to adjust the retrieved partial adaption coefficients so that they become their corresponding complete adaption coefficients. This can be implemented by making each partial adaption coefficient equal to its corresponding complete adaption coefficient less a constant. The constant can then be added to each partial adaption coefficient before it is applied to the consequential signal. In a preferred embodiment, at least a substantial proportion of the complete adaption coefficients lie near a particular value and that value is used as the constant.

In another embodiment, the partial adaption coefficients are applied to the consequential signal and the correction for the use of partial adaption coefficients is achieved by combining the adjusted (i.e. after treatment with the partial coefficients) and unadjusted (i.e. before treatment with the partial coefficients) versions of the consequential signal. Preferably, the unadjusted and adjusted versions of the consequential signal are time aligned before combination. The unadjusted and adjusted versions of the consequential signal may be scaled relative to one another before combination.

In one embodiment, the coefficients to be used are selected from the group by an indexing signal. Advantageously, the indexing signal can be adjusted to correct for memory effects in the signal handling equipment.

According to a second aspect, the invention provides apparatus for correcting signal distortion by employing a group of adaption coefficients to adjust a consequential signal to ameliorate distortion in an output signal produced by signal handling equipment in

response to an input signal, the apparatus comprising means for selecting coefficients to use in the adjustment of the consequential signal using an indexing signal, and means for adjusting the indexing signal to correct for memory effects in the signal handling equipment.

The invention also consists in a method of correcting signal distortion by employing a group of adaption coefficients to adjust the consequential signal to ameliorate distortion in an output signal produced by signal handling equipment in response to an input signal, the method comprising selecting coefficients to use in the adjustment of the consequential signal using an indexing signal, and adjusting the indexing signal to correct for memory effects in the signal handling equipment.

The adjustment of the indexing signal may be achieved by subjecting it to a time-shift or to filtering.

In a preferred embodiment, the distortion correction is the linearisation of the signal handling equipment. Preferably, this linearisation is by way of predistortion, in which case the consequential signal is the input signal to the signal handling equipment. In another embodiment, the linearisation is by way of a feedforward arrangement, in which case the input signal to the signal handling equipment is sensed and the consequential signal is the sensed input signal which is combined with the output signal subsequent to adjustment using the adaption coefficients.

In preferred embodiments, the signal handling equipment is an amplifier or an arrangement of amplifiers.

By way of example only, certain embodiments of the invention will now be described with reference to the accompanying figures, in which:

Figure 1a is a block diagram of a conventional digital to RF transmitter with digital predistortion;

Figure 1b illustrates the architecture of the predistorter block in Figure 1a when the input signal is in digital IF (intermediate frequency) form;

Figure 1c illustrates the architecture of the predistorter block in Figure 1a when the input signal is in IQ format;

Figure 2a is a block diagram of a digital to RF transmitter with digital predistortion according to the invention;

Figure 2b illustrates the architecture of the predistorter block in Figure 2a;

Figure 2c illustrates an alternative form for the predistorter block in Figure 2a;

Figure 3a is block diagram of a digital to RF transmitter with digital predistortion according to another embodiment of the invention;

Figure 3b illustrates the architecture of the predistorter block in Figure 3a; and

Figure 3c illustrates an alternative form for the predistorter block in Figure 3a.

A block diagram of a conventional digital to RF transmitter with digital predistortion is shown in Figure 1a. In this system, a digital input is assumed, although an RF input could be accommodated by adding a downconversion function together with analog to digital conversion (A/D) to convert an RF input into a digital input.

The RF power amplifier (RFPA) 10, and the upconverter (U/C) 12 to a lesser extent, exhibit non-linear characteristics producing amplitude and phase distortion. The digital predistorter 14 overcomes these non-linearities by modifying the digital inputs to form a new digital data stream such that there is minimal difference between the two inputs at the error estimation and adaptation block 16. This modified data stream is converted to an analog signal by digital to analog convertion (D/A) at 20 and up-converted at 12 to the required RF frequency at low power. The power amplifier 10 then amplifies the low power

RF signal producing the majority of the signal distortion. A sample of the output power is fed back from 22 to the error estimation block 16 via a downconverter (D/C) 24 and analog to digital conversion (A/D) at 26.

The architectures for the digital predistortion block 14 shown in Figures 1b and 1c show the input signal being processed in quadrature though it is also possible to process in amplitude and phase (polar coordinates) also. Either allows both amplitude and phase distortion characteristics to be linearised.

In the pre-distorter block architectures, the digital input samples are weighted (multiplied) by the values contained in the look-up tables 28, 30. The Figure 1c architecture has the disadvantage of requiring more multipliers due to the IQ format of the input signal but has the advantages of possibly running at a lower clock frequency and more flexibility in the upconversion process 12. The appropriate lookup table (LUT) value for a given sample is selected from the table by means of a table index. This indexation is typically based on the input envelope power as shown here (at 27), although other possibilities exist (e.g. input envelope amplitude).

The inefficient use of digital hardware in this prior art is manifested in the "I look-up table" (LUT$_i$) 28 whose values are centred about unity. As the LUT is located in the main signal path, its resolution must account for both the linear and non-linear aspects of the desired response. For example, if a given sample required a 5% increase in gain in order to compensate for the amplifier non-linearity present at that power level, the look-up table would contain a value of 1.05000 – multiplying this with the input sample would yield the desired gain expansion. However to avoid introducing noise resulting from the discrete number of levels in the LUT its depth must be deep, typically 12-14 bits in most digital communications applications. This requires a significant amount of digital hardware resource to store this information at this accuracy and also in the multiply and add steps that follow.

The embodiments that follow reduce the digital hardware requirement by only requiring the gain error part of the LUT to be stored (0.05000 in the example above instead of 1.05000)

i.e. removing the linear part of the multiplication. This concentrates the digital system resolution where it is needed in accurately creating the gain compression/expansion required and reduces the number of bits in the LUT by 3-4 typically.

An additional advantage conferred by some of the following embodiments is that memory effects are to be predistorted; this is not possible in the Figure 1 architecture where the linear and gain compression/expansion terms are combined in the one table.

The architecture of Figure 2a which separates the linear gain part from the gain error part (compression/expansion) of the characteristic incorporates a digital delay 32 in parallel with the predistortion processing 14. This delay 32 has unity gain and serves to time-align the linear signal with the error signal at the summing junction 34. Since this processing occurs digitally, it is possible to ensure that this alignment occurs precisely, hence preserving the same linearisation bandwidth as that of the prior art.

As shown in Figure 2b, the LUT$_1$ 36 now merely contains the value of the gain expansion (or compression) required at a given power level (e.g. the 5% expansion mentioned above) and hence the full resolution of the system may be used to represent this (e.g. 5%) value reducing the number of bits used in the LUT$_1$ by 3-4 typically. This is illustrated in Figure 2b where the LUT$_1$ table is shown centred around 0 instead of 1 as in Figure 1b. Note that the predistorter architecture of Figure 2b is also suitable for digital IQ input although it has not been illustrated here. Briefly, the predistorter architecture in Figure 2b would need the input 90° splitter 38 taken out and two additional multipliers with subtractor added as illustrated in Figure 1c. A similar conversion from digital IF to digital IQ format can be made for all of the following embodiments of the predistorter block architecture.

The operation of the remainder of the system of Figure 2a is identical to that described with reference to Figure 1a, with the exception that the error estimation and adaptation function is now only required to calculate the desired gain expansion or compression and not the overall transfer characteristic. It can therefore operate at the required (optimum) resolution.

The Figure 2a architecture is also ideal for the inclusion of memory correction, which is particularly important for wide bandwidth systems. The predistorter block 14 can take the form shown in Figure 2c to achieve this. The filters 40, 42 preceding the I and Q lookup tables typically have different characteristics to allow for different memory characteristics in the amplitude and phase distortion processes in the power amplifier (PA) 10. These filters delay the input envelope to the LUTs to match those processes taking place in the PA 10. They may also or additionally reshape the input envelope supplied to the LUTs. The important feature of the Figure 2a is the separation of the linear and error correction parts of the gain term that allows the error correction parts to be delayed and filtered relative to the linear part. This architecture is capable of predistorting for imbalances of the distortion products that are common in power amplifiers.

Filter$_I$ 40 and Filter$_Q$ 42 could also be placed immediately after their respective LUTs though the preferred embodiment is in the position shown.

An alternative architecture is shown in Figures 3a to 3b. This architecture accomplishes the requirement of separating the linear and error correcting parts of the gain without the delayed input signal path. Instead, the separation is achieved by adding at 44 a constant to the output of the LUT$_I$ output before multiplication process 46. This alternative architecture offers the same advantages over the prior art as those of Figure 2 in being able to reduce the size of the LUT significantly and to allow for memory effect correction (Figure 3b).

The differences between the architectures of Figures 2 and 3 lie in the small differences in size of the multipliers and adders.

The invention has been described above in the context of applying partial coefficients to a consequential signal to ameliorate distortion. Of course, it will be apparent to the skilled person that the invention also extends to using partial coefficients in some other kind of signal processing operation performed on a target signal, with a correction for the fact that the retrieved coefficients are partial to give the effect that the signal processing operation has been done using complete coefficients.

CLAIMS

1. Apparatus for correcting signal distortion by employing a group of adaption coefficients to adjust a consequential signal to ameliorate distortion in an output signal produced by signal handling equipment in response to an input signal, the apparatus comprising means for using partial adaption coefficients in the adjustment of the consequential signal and means for correcting for the fact that the retrieved coefficients are partial to give the effect that adjustment of the consequential signal has been done using complete adaption coefficients.

2. Apparatus according to claim 1, wherein the retrieved partial adaption coefficients are converted into complete adaption coefficients before they are used in the adjustment of the consequential signal.

3. Apparatus according to claim 2, wherein the partial attached coefficients are calculated relative to a constant and each partial adaption coefficient equals its corresponding complete adaption coefficient less the constant.

4. Apparatus according to claim 3, wherein the value chosen for the constant is a value near which a substantial proportion of the complete adaption coefficients lie.

5. Apparatus according to claim 1, wherein the partial adaption coefficients are applied to the consequential signal and the correction for the use of partial adaption coefficients is achieved by combining the adjusted version of the consequential signal with an unadjusted version of the consequential signal.

6. Apparatus according to any one of claims 1 to 5, wherein the coefficients to be used are selected from the group by an indexing signal.

7. Apparatus according to claim 6, wherein the indexing signal can be adjusted to correct for memory effects in the signal handling equipment.

8. Apparatus for correcting signal distortion by employing a group of adaption coefficients to adjust a consequential signal to ameliorate distortion in an output signal produced by signal handling equipment in response to an input signal, the apparatus comprising means for selecting coefficients to use in the adjustment of the consequential signal using an indexing signal, and means for adjusting the indexing signal to correct for memory effects in the signal handling equipment.

9. Apparatus according to claim 7 or 8, wherein the adjustment of the indexing signal is achieved by subjecting it to at least one of time shifting or filtering.

10. Apparatus according to any one of claims 1 to 9 wherein the distortion correction is the linearisation of the signal handling equipment.

11. Apparatus according to claim 10, wherein the linearisation is by way of predistortion and the consequential signal is the input signal to the signal handling equipment.

12. Apparatus according to claim 10, wherein the linearisation is by way of a feedforward arrangement and the input signal to the signal handling equipment is sensed to provide the consequential signal, and the consequential signal is, subsequent to its adjustment using the adaption coefficients, combined with the output signal.

13. Apparatus according to any one of claims 1 to 11, wherein the signal handling equipment comprises amplifying means.

14. A method of correcting signal distortion by employing a group of adaption coefficients to adjust a consequential signal to ameliorate distortion in an output signal produced by signal handling equipment in response to an input signal, the method comprising using partial adaption coefficients in the adjustment of the consequential signal and correcting for the fact that the retrieved coefficients are partial to give the effect that adjustment of the consequential signal has been done using complete adaption coefficients.

15. A method according to claim 14, wherein the retrieved partial adaption coefficients are converted into complete adaption coefficients before they are used in the adjustment of the consequential signal.

16. A method according to claim 15, wherein the partial attached coefficients are calculated relative to a constant and each partial adaption coefficient equals its corresponding complete adaption coefficient less the constant.

17. A method according to claim 16, wherein the value chosen for the constant is a value near which a substantial proportion of the complete adaption coefficients lie.

18. A method according to claim 14, wherein the partial adaption coefficients are applied to the consequential signal and the correction for the use of partial adaption coefficients is achieved by combining the adjusted version of the consequential signal with an unadjusted version of the consequential signal.

19. A method according to any one of claims 14 to 18, wherein the coefficients to be used are selected from the group by an indexing signal.

20. A method according to claim 19, wherein the indexing signal can be adjusted to correct for memory effects in the signal handling equipment.

21. A method of correcting signal distortion by employing a group of adaption coefficients to adjust a consequential signal to ameliorate distortion in an output signal produced by signal handling equipment in response to an input signal, the method comprising selecting coefficients to use in the adjustment of the consequential signal using an indexing signal, and adjusting the indexing signal to correct for memory effects in the signal handling equipment.

22. A method according to claim 20 or 21, wherein the adjustment of the indexing signal is achieved by subjecting it to at least one of time shifting or filtering.

23. A method according to any one of claims 14 to 22, wherein the distortion correction is the linearisation of the signal handling equipment.

24. A method according to claim 23, wherein the linearisation is by way of predistortion and the consequential signal is the input signal to the signal handling equipment.

25. A method according to claim 23, wherein the linearisation is by way of a feedforward arrangement and the input signal to the signal handling equipment is sensed to provide the consequential signal, and the consequential signal is, subsequent to its adjustment using the adaption coefficients, combined with the output signal.

26. A method according to any one of claims 14 to 25, wherein the signal handling equipment comprises amplifying means.

27. A method of correcting signal distortion, substantially as hereinbefore described with reference to the accompanying figures.

28. Apparatus for correcting signal distortion, substantially as hereinbefore described with reference to the accompanying figures.